Effects of SiC_p on microstructures of semi-solid extruded AZ91D magnesium alloys in recrystallization process

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Abstract: AZ91D and 8.5vol.% SiC_p/AZ91D magnesium matrix composites were fabricated by a semi-solid extruded processing method, and treated with solution and aging heat treatment. The effects of SiC_p on the microstructures of the semi-solid extruded AZ91D magnesium alloy during recrystallization were studied by observing and analyzing the microstructure evolution during extrusions and heat treatments. The results show that the addition of SiC_p inhibits the dynamic recrystallization of AZ91D during the semi-solid extrusion with only 26% of the volume fraction of recrystallization. Furthermore, the addition of SiC_p refines the sizes of grains and second phases, and upgrades the volume fraction of second phase. After solution and aging treatment, the recrystallization continues, and the addition of SiC_p promotes the recrystallization and the recrystallized microstructure is much more stable. Meanwhile, the sizes of grains and second phases continue to be refined, and the volume fraction of second phases continues to increase.

Key words: SiC_p/AZ91D; composites; semi-solid extrusion; recrystallization; microstructure

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1 Introduction

Magnesium alloy is the lightest non-ferrous metal material with light weight, high specific strength, and good wear resistance. In recent years, it has been widely used in lightweight fields such as automobile and airplane components^[1-3]. Due to generally inferior mechanical properties of magnesium alloy compared to iron and steel materials, the promotion of magnesium alloy mechanical properties such as tensile property and hardness is significant. The prerequisite for improving those properties is an excellent microstructure. Wang et al.^[4] studied the effects of process parameters on the microstructures of AZ91D prepared by near-liquidus casting, the results indicated that the microstructure grains tended to form a rosette firstly, and then rosette grains were transformed into near-globular grains with the decrease of pouring temperature during near-liquidus casting. Guo et al.^[5] prepared a (SiC+TiC)_p/AZ91

nanocomposite by semi-solid stirring and ultrasonic treatment, which was extruded at 270 °C with different extrusion speeds. The results showed that SiC+TiC and dynamically precipitated Mg₁₇Al₁₂ phase that hindered the grain boundary movement were conducive to a grain refinement, and the grain size decreased with the decrease of extrusion speed. Wang et al.^[6] studied the effect of hot extrusion on SiC_p/AZ91 magnesium matrix composites, and found that hot extrusion could promote the distribution of SiC as well as dynamic recrystallization, thereby refining the grain size. Although the magnesium alloy undergoes recrystallization and is in a low energy state, the strain energy exists in the deformed and strengthened microstructures, so the appropriate heat treatment is necessary to obtain a more stable microstructure. The investigation of Zheng et al.^[7] on the aging precipitation behavior of SiC_w/AZ91 indicated that the discontinuous Mg₁₇Al₁₂ phases were precipitated preferentially at the SiC_w-AZ91 interface under the condition of solution and aging treatment. Sun et al.^[8] studied the aging behavior of SiC_p/AZ91, and found that the aging treatment promoted the precipitation of second phase and refined grain size, thus generating aging strengthening on material properties. However, corresponding research works

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on the combination of deformation strengthening and heat treatment strengthening of magnesium matrix composites are very limited. Thus, this experiment combined the semi-solid extrusion strengthening and the enhanced phase strengthening of the AZ91D magnesium, and further investigated the effects of SiC particles on recrystallization microstructure evolutions during extrusion and heat-treatment. The influence of the manufacturing process on the microstructure of the composites was investigated deeply, which provided a method for researching automobile lightweight and low-energy on the micro-structure level. SiC_p/AZ91D magnesium matrix composites with good microstructure and properties prepared by semi-solid extrusion can broaden the application of magnesium alloys.

2 Experimental procedure

AZ91D magnesium alloy was selected as the matrix alloy, in which the Al content was 8.5wt.%–9.5wt.%, Zn content was 0.45wt.%–0.9wt.% and the balance element was Mg. The preparation processes of the semi-solid billets were as follows: AZ91D melt was cooled to 670 °C, then 10 μm 8.5vol.% SiC_p was added and held for 5 min at 670 °C. The melt was then cooled to 575 °C and mechanically stirred at 400 r·min⁻¹ for 30 min. The melt was then heated to 720 °C, and stirred again at 400 r·min⁻¹ for 5 min. Then, the melt was cooled to 595 °C and held for 30 min. Finally, it was poured into a mold preheated at 200 °C to obtain a semi-solid billet.

The semi-solid extrusion was carried out on a 200-ton extruding machine with an extrusion temperature of 575 °C. After holding for 30 min, an extrusion was done at the pressure of 2,000 kN and speed of 1 mm·s⁻¹. Finally, the samples were

treated by solution at 415 °C for 24 h (T4) and aging at 220 °C for 8 h (T6).

The AZ91D and SiC_p/AZ91D samples were corroded by 4% nitric acid alcohol solution. Microstructure and composition were observed and analyzed by Leica 6000M optical microscopy and Tescan scanning electron microscopy. The phase constitution of samples was analyzed by XRD with Bruker D8ADVANCE X-ray diffractometer. The recrystallization degree, grain orientation and pole figure were analyzed by Helios Nanolab 600i electron backscatter diffraction system. The phase size and phase volume fraction were measured by Image Pro Plus 5.0 software. The surface of the samples parallel to the direction of extrusion was observed.

3 Results and discussion

Figure 1 shows the XRD analysis of semi-solid extruded AZ91D and SiC_p/AZ91D under the T4 and T6 treatments. The XRD patterns in Fig. 6(a) show that the AZ91D contains α -Mg and Mg₁₇Al₁₂ [9], in which the peak value of α -Mg is higher than the Mg₁₇Al₁₂. The higher peak value, the higher crystallinity degree of the corresponding phase. Figure 1(b) shows that after the addition of SiC_p, the SiC_p/AZ91D contains α -Mg, Mg₁₇Al₁₂, and SiC reinforcement phase. The peak value of SiC is very low, and the diffraction peaks of α -Mg and Mg₁₇Al₁₂ are reduced due to the addition of SiC, which indicates that the addition of SiC limits the crystallinity of α -Mg and Mg₁₇Al₁₂. However, comparing the XRD patterns of AZ91D or SiC_p/AZ91D under different heat treatments, it can be seen that T4 and T6 heat treatment have no significant effect on the diffraction patterns, and no new phases are generated in the microstructures.

Fig. 1: XRD patterns of AZ91D (a) and SiC_p/AZ91D (b) under different states

Figure 2 shows the SEM and corresponding EDS images of AZ91D and SiC_p/AZ91D prepared by the semi-solid extrusion. Figures 2(a) and (b) show that the point-like and island-like Mg₁₇Al₁₂ phases (P-Mg₁₇Al₁₂ and I-Mg₁₇Al₁₂) are uniformly distributed along the grain boundaries in AZ91D, and the point-like Mg₁₇Al₁₂ phases surround the island-like Mg₁₇Al₁₂ phases. Figures 2(c) and (d) show the SiC particles in the SiC_p/AZ91D microstructures occupy the grain boundaries with necklace

shape, while the point-like and island-like Mg₁₇Al₁₂ phases are still distributed along the grain boundaries, and the point-like Mg₁₇Al₁₂ phases tend to be adhered to SiC particles. Comparing Figs. 2(a) and (b) with Figs. 2(c) and (d), the addition of SiC_p enhances a dynamic precipitation of Mg₁₇Al₁₂ phase.

Figure 3 shows the morphology and microstructure of SiC_p/AZ91D after T6 treatment under high magnification of SEM and corresponding EDS with respect to Mg₁₇Al₁₂ phase.

Fig. 2: SEM and EDS images after semi-solid extrusion: (a), (b) AZ91D; (c), (d) SiC_p/AZ91D

The morphology and distribution orientation of a point-like, a lamellar and an island-like second phase can be clearly observed, and the element distributions of Mg and Al are shown in Fig. 3(b). Results show that the Mg₁₇Al₁₂ precipitates in a large amount with a certain orientation at a small range after further solution and aging treatment. Through observing the distributed orientations of island-like, lamellar and point-like Mg₁₇Al₁₂, it is evident that the morphology of Mg₁₇Al₁₂

phases is evolved from island-like to lamellar and then to point-like because of the effect of T6 heat treatment.

SEM images of semi-solid extruded AZ91D and SiC_p/AZ91D under different heat treatments are shown in Fig. 4. Comparing Figs. 4(a)–(c) with Figs. 4(d)–(f), the addition of SiC increases the number of Mg₁₇Al₁₂ and refines the grain size of Mg₁₇Al₁₂ at the same time. This is because the addition of SiC increases the number of dislocations and grain

Fig. 3: SEM and EDS of SiC_p/AZ91D about Mg₁₇Al₁₂ phase after T6 treatment: (a) SEM; (b) corresponding EDS of (a)

boundaries dramatically, and the grain boundaries can be used as a channel for a rapid diffusion of atoms, which can improve the nucleation rate of precipitates^[10]. The distribution of SiC_p in $\text{SiC}_p/\text{AZ91D}$ is shown in Figs. 4(d)–(f). With the progress of the solution and aging treatment, the distribution of SiC_p gradually disperses along grain boundaries but the size and morphology are not changed much under the T4 and T6 heat treatments. This may be due to the further recrystallization of the microstructure caused by the solution and aging treatment, and that the recrystallized grains facilitate the SiC movement

at the grain boundaries during nucleation and growth, and thus some aggregated SiC particles are dispersedly distributed. In addition, the secondary precipitates (lamellar and point-like) of $\text{Mg}_{17}\text{Al}_{12}$ phase are gradually full of the microstructure after T6 treatment, along with a large number of precipitates of $\text{Mg}_{17}\text{Al}_{12}$ in the vicinity of SiC_p , while in the grain boundary with a small amount of SiC_p , there are fewer precipitates. This is because particle deformation zones are formed around SiC_p after the semi-solid extrusion, which can promote the formation of secondary precipitates during the heat treatments^[7].

Fig. 4: SEM images of semi-solid extruded AZ91D (a–c) and $\text{SiC}_p/\text{AZ91D}$ (d–f) under different states: (a), (d) as-extruded; (b), (e) T4 treatment; (c), (f) T6 treatment

The grain sizes of the samples were measured and the results are shown in Fig. 5. It can be seen that the T4 and T6 heat treatments and the addition of SiC_p greatly reduces the grain sizes of the semi-solid extruded AZ91D. After T6 treatment, the grain size of $\text{SiC}_p/\text{AZ91D}$ reaches the minimum of 15.78 μm . However, the grain refinement effect of $\text{SiC}_p/\text{AZ91D}$ is not very obvious after the T4 and T6 heat treatment. This is because the addition of SiC_p leads to a large number of dislocations accumulation, and the limited deformation time causes dislocations which cannot be offset or merged completely. Therefore, the sites of recrystallization nucleation increase and the boundaries meet during the growth of new grains, which limits the growth of grains and leads to a grain refinement. However, a further solution and aging treatment can release the accumulated storage energy during deformation, which is beneficial to grain growth. Therefore, grain refinement

Fig. 5: Comparison of grain sizes of semi-solid extruded AZ91D and $\text{SiC}_p/\text{AZ91D}$ under different states

and grain growth offset each other, resulting in no obvious change in the grain size of $\text{SiC}_p/\text{AZ91D}$ after the T4 and T6 heat treatment^[11].

To further investigate the effects of SiC_p on the microstructures of the semi-solid extruded AZ91D, the size and volume fraction of second phase in semi-solid extruded AZ91D and $\text{SiC}_p/\text{AZ91D}$ under different heat treatments were measured, as shown in Table 1. The results show that the addition of SiC_p reduces the sizes of the second phase and greatly increases its volume fractions. This is because there are many particle deformation zones caused by SiC particles in the microstructure of composites, and SiC particles can refine grain sizes, thus generating a large amount of dislocations which promote the production of $\text{Mg}_{17}\text{Al}_{12}$. In addition, the dispersed SiC also provides the heterogeneous nuclei for the second phase. The subsequent solution and aging treatment further decreases the sizes of the second phase and increases its volume fraction continuously, and generates more dislocations^[12, 13], which further promotes the nucleation of the second phase. According to the analysis results shown in Figs. 4 and 5, although the second phase are refined and its volume fraction is increased due to the addition of SiC_p , there are still some concentrated regions of SiC_p and coarse point-like precipitates

in the microstructure, resulting in an insignificant refining effect of the second phase^[14], so the subsequent solution and aging treatment process is necessary. After T6 treatment, SiC is dispersed and the coarse precipitate is refined. As can be seen from Table 1, the second phase size of $\text{SiC}_p/\text{AZ91D}$ is greatly decreased to $0.16\ \mu\text{m}$ and its volume fraction is greatly increased to 26.87%.

The recrystallization degrees and corresponding recrystallized volume fraction graphs of semi-solid extruded AZ91D and $\text{SiC}_p/\text{AZ91D}$ with different heat treatments are respectively shown in Figs. 6 and 7, where the color blue represents recrystallized grains, yellow represents sub-crystal grains, and red represents deformed grains. According to Figs. 6(a) and (d), the microstructures of AZ91D undergo dynamic recrystallization during the semi-solid extrusion, and its volume fraction exceeds 60%. However, the recrystallization during the semi-solid extrusion is incomplete, and there are some deformed grains whose volume fraction exceeds 25% while the volume fraction of sub-crystal grains reaches 12%. However, the subsequent solution and aging treatment [Figs. 6(b), (e) and Figs. 6(c), (f)]

Table 1: Second phase size and volume fraction of semi-solid extruded AZ91D and $\text{SiC}_p/\text{AZ91D}$ under different states

$\text{Mg}_{17}\text{Al}_{12}$ phase	AZ91D			$\text{SiC}_p/\text{AZ91D}$		
	As-extruded	T4	T6	As-extruded	T4	T6
Size (μm)	0.69	0.59	0.50	0.42	0.22	0.16
Volume fraction (%)	8.15	17.14	23.05	16.12	20.49	26.87

Fig. 6: Recrystallization degree and corresponding volume fraction bar chart of semi-solid extruded AZ91D under different treatments: (a), (d) as-extruded; (b), (e) T4 treatment; (c), (f) T6 treatment

Fig. 7: Recrystallization degree and corresponding volume fraction bar chart of semi-solid extruded $\text{SiC}_p/\text{AZ91D}$ under different treatment conditions: (a), (d) as-extruded; (b), (e) T4 treatment; (c), (f) T6 treatment

causes the recrystallization to continue to occur, and the deformed grains almost disappear but not completely, while the volume fraction of sub-crystal grains increases.

Compared with Fig. 6, the recrystallization microstructures of semi-solid extruded $\text{SiC}_p/\text{AZ91D}$ in Fig. 7 show that the addition of SiC_p makes the dynamic recrystallization in the extrusion process more incomplete, the volume fraction of recrystallized grains is only 26%, while the volume fraction of deformed grains exceeds 60% before solution and aging treatment. Nevertheless, the subsequent solution and aging treatment causes the recrystallization process to continue, and the volume fraction of deformed grains is reduced to about 1%, but there are a large number of sub-crystal grains in the microstructures, and the volume fraction reaches about 30%. The above results show that under the semi-solid extrusion temperature, the second phase precipitates in magnesium matrix and counteracts the softening effect of dynamic recrystallization and inhibits the occurrence of dynamic recrystallization^[15]. Moreover, the addition of SiC leads to a larger number of dislocations and greatly promotes the precipitation of $\text{Mg}_{17}\text{Al}_{12}$, which also inhibiting the occurrence of dynamic recrystallization.

By observing the recrystallized microstructures in Figs. 6 and 7, it can be seen that the recrystallized grains nucleate and grow at the grain boundaries and then gradually replace deformed grains. This is because after extrusion, the grain boundaries are the aggregation areas of $\text{Mg}_{17}\text{Al}_{12}$ and SiC_p , and the stored deformation energy nearby is very high, which can provide driving forces for the occurrence of

dynamic recrystallization and lead to the growth of dynamic recrystallization grains in this nucleation^[16]. In addition, due to the compatibility of deformation between the adjacent grains, the recrystallization boundaries are serrated^[17]. Most of the fine serrated grains grow into those grains around the boundaries of large grains, while the sub-crystal grains also expand toward the crystal boundaries^[18], which indicate that the recrystallization grains arched and nucleated at grain boundaries are caused by a local grain boundary migration. Since the temperature of the subsequent solution treatment (T4) is higher than the minimum recrystallization temperature (about 100 °C) of AZ91D, the recrystallization continues to happen. According to the analysis results in Fig. 4, although the temperature of solution and aging treatment (T6) makes the grain recrystallization no longer continue to occur, the process is accompanied by a large amount of secondary precipitation of $\text{Mg}_{17}\text{Al}_{12}$ phase, and their pinning actions on grain boundaries further rounds and refines the grains^[19].

Figure 8 shows the grain orientation distribution diagrams of semi-solid extruded AZ91D and $\text{SiC}_p/\text{AZ91D}$, in which a corresponding polar diagram is embedded, and white lines are low-angle grain boundaries ($< 5^\circ$). By observing Figs. 8(a) and (d), it can be seen that the addition of SiC_p causes a sharp increase in the number of low angle grain boundaries. In addition, dynamic recrystallization nucleation occurs at the original high-angle grain boundary, rather than in the deformation zone or inside the original grains^[17]. The dynamic recrystallization requires a sufficient deformation period and closed loop at high-angle grain boundaries, while the

Fig. 8: Grain orientation distribution of semi-solid extruded AZ91D and SiC_p/AZ91D under different states: (a), (d) as-extruded; (b), (e) T4 treatment; (c), (f) T6 treatment

addition of SiC_p creates a particle aggregation region, which does not easily form a closed loop between grain boundaries, resulting in incomplete recrystallization^[17], and thus a sharp increase in the number of low-angle grain boundaries. After the subsequent solution and aging treatment, the number of high-angle grain boundaries greatly increases, the low-angle grain boundaries almost disappear, and then the grain orientations gradually become disorganized. This is because the storage energy of grain boundaries after extrusion can be released by heat treatment, which leads to a grain boundaries migration and a sub-grain rotation, and promotes the transformation of low-angle grain boundaries into the high-angle grain boundaries^[20]. In addition, it can be seen that the low-angle grain boundaries exist between grains with close orientation, which indicates that during recrystallization, the grain boundary energy releases from the grain boundary and promotes recrystallization. Thus, it can be seen that the recrystallization microstructure of SiC_p/AZ91D is more stable than that of AZ91D after T6 heat treatment.

Figure 9 shows the pole figures of semi-solid extruded AZ91D and SiC_p/AZ91D under different treatments. The peak value of semi-solid extruded AZ91D appears extremely strong near Y1 direction and the matrix texture is obvious ($[2\bar{1}10]$), while the peak value of semi-solid extruded SiC_p/AZ91D deflects about 90° towards X1 direction and the peak value is strong. After T6 treatment, the contour line in the polar

diagram changes from single-peak to multi-peak, and the peak value also decreases with the heat treatment. The peak strength of semi-solid extruded SiC_p/AZ91D after solution and aging treatment is much lower than that of AZ91D. Those results show that the addition of SiC_p promotes recrystallization during solution and aging treatment, and the basal texture is strongly weakened^[21], the interface energy can be reduced, and the microstructure is more stable, which corresponds to the analysis of Fig. 8.

4 Conclusions

(1) The addition of SiC_p and T6 treatment greatly increases the precipitation of Mg₁₇Al₁₂ phase, and refines the grain and second phase. After T6 treatment, the grain size of SiC_p/AZ91D reaches the minimum of 15.78 μm, the phase size of Mg₁₇Al₁₂ reaches the minimum of 0.16 μm, and its volume fraction reaches the maximum of 26.87%.

(2) During semi-solid extrusion of AZ91D, the local migration of grain boundaries makes the most of dynamic recrystallization grains are nucleated by arching grain boundaries. The addition of SiC_p leads to a large number of dislocations and particle aggregation regions. Within a limited extrusion time, the dynamic recrystallization occurs incompletely, and reaches only 26%.

(3) The addition of SiC deflects the peak value of the semi-

Fig. 9: Pole figures of semi-solid extruded AZ91D and SiC_p/AZ91D under different states: (a), (b) as-extruded; (c), (d) T4 treatment; (e), (f) T6 treatment

solid extruded AZ91D pole figure by being 90° towards the X1 direction, the peak value of the pole figure is significantly weakened after T6 treatment. The grain microstructure is more stable than that of AZ91D under the same heat treatment.

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References

- [1] Xin R L, Wang B S, Chen X P, et al. Examination of dynamic recrystallization during compression of AZ31 magnesium. *Science in China Series E: Technological Sciences*, 2009, 52(1): 176–179.
- [2] Jiang J, Godferyb A, Liu Q. Microstructure and texture evolution during warm compression of the magnesium alloy AZ31. *Science in China Series E: Technological Sciences*, 2009, 52(1): 186–189.

- [3] Bonnah R C, Fu Y, Hao H. Microstructure and mechanical properties of AZ91 magnesium alloy with minor additions of Sm, Si and Ca elements. *China Foundry*, 2019, 16(5): 319–325.
- [4] Wang K, Liu C M, Zhai Y B, et al. Microstructural characteristics of near-liquidus cast AZ91D alloy during semi-solid die casting. *Transactions of Nonferrous Metals Society of China*, 2010, 20(2): 171–177.
- [5] Guo Y C, Nie K B, Kang X K, et al. Achieving high-strength magnesium matrix nanocomposite through synergistical effect of external hybrid (SiC+TiC) nanoparticles and dynamic precipitated phase. *Journal of Alloys and Compounds*, 2019, 771: 847–856.
- [6] Wang X J, Hu X S, Nie K B, et al. Hot extrusion of SiC_p/AZ91 Mg matrix composites. *Transactions of Nonferrous Metals Society of China*, 2012, 22(8): 1912–1917.
- [7] Zheng M Y, Wu K, Kamado S, et al. Aging behavior of squeeze cast SiC_w/AZ91 magnesium matrix composite. *Materials Science and Engineering: A*, 2003, 348: 67–75.
- [8] Sun X F, Wang C J, Deng K K, et al. Aging behavior of AZ91 matrix influenced by 5 μm SiC_p: Investigation on the microstructure and mechanical properties. *Journal of Alloys and Compounds*, 2017, 727: 1263–1272.
- [9] Qi M F, Kang Y L, Yan Y, et al. Comparison of microstructure and mechanical properties of AZ91D alloy formed by rheomolding and high-pressure die casting. *Journal of Materials Engineering and Performance*, 2015, 24(10): 3826–3834.
- [10] Choi H J, Min B H, Shin J H, et al. Strengthening in nanostructured 2024 aluminum alloy and its composites containing carbon nanotubes. *Composites Part A: Applied Science and Manufacturing*, 2011, 42(10): 1438–1444.
- [11] Wang C J, Deng K K, Li J C, et al. Flow stress and deformation behavior of fine-grained Mg matrix influenced by bimodal size SiC_p. *Journal of Materials Research*, 2018, 33(12): 1723–1732.
- [12] Chrominski W, Lewandowska M. Precipitation phenomena in ultrafine grained Al-Mg-Si alloy with heterogeneous microstructure. *Acta Materialia*, 2016, 103: 547–557.
- [13] Yang X, Li K, An X, et al. Influence of deformation microstructure on the precipitation behaviors of an Al-4Mg-0.3 Cu alloy. *Journal of Alloys and Compounds*, 2017, 695: 2238–2245.
- [14] Nie K, Zhu Z, Deng K, et al. Hot deformation behavior and processing maps of sic nanoparticles and second phase synergistically reinforced magnesium matrix composites. *Nanomaterials*, 2019, 9(1): 57.
- [15] Zhu D Y, Zhen L, Hu W H, et al. Effect of strain on DRX of 7050 aluminum alloy during extrusion at high temperature. *Rare Metals*, 2007, (S1): 338–343.
- [16] Wang X J, Hu X S, Wang Y Q, et al. Microstructure evolutions of SiC_p/AZ91 Mg matrix composites during hot compression. *Materials Science and Engineering: A*, 2013, 559: 139–146.
- [17] Xie B C, Zhang B Y, Ning Y Q, et al. Mechanisms of DRX nucleation with grain boundary bulging and subgrain rotation during the hot working of nickel-based superalloys with columnar grains. *Journal of Alloys and Compounds*, 2019, 786: 636–647.
- [18] Wu Y P, Zhang X M, Deng Y L, et al. Dynamic recrystallization mechanisms during hot compression of Mg-Gd-Y-Nd-Zr alloy. *Transactions of Nonferrous Metals Society of China*, 2015, 25(6): 1831–1839.
- [19] Sun X F, Wang C J, Deng K K, et al. High strength SiC_p/AZ91 composite assisted by dynamic precipitated Mg₁₇Al₁₂ phase. *Journal of Alloys and Compounds*, 2018, 732: 328–335.
- [20] Li J S, Cheng G J, Yen H W, et al. Microstrain and boundary misorientation evolution for recrystallized super DSS after deformation. *Materials Chemistry and Physics*, 2020, 246: 122815.
- [21] Liu Y X, Li Y X, Zhang H, et al. Influence of twinning-induced recrystallization on texture evolution in a high strain rate compressed Mg-Zn alloy. *Materials Characterization*, 2020, 162: 110192.